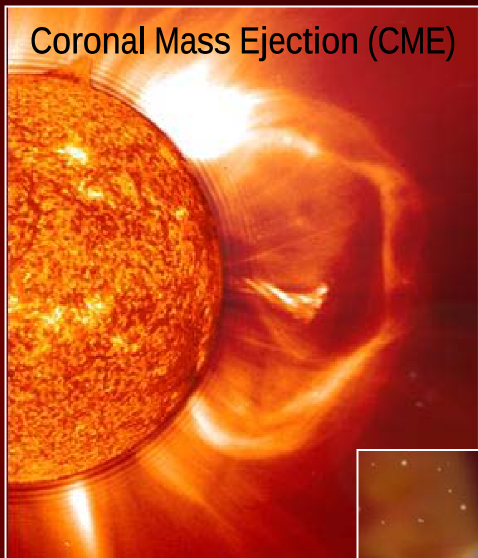
Modeling of Geomagnetically Induced Currents (GICs) – Current State of the Art

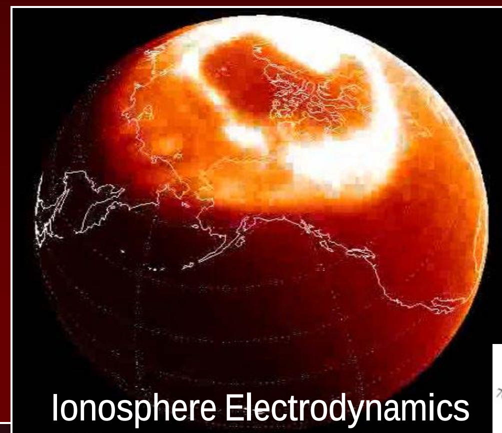
J. Patrick Donohoe, Ph.D., P.E.

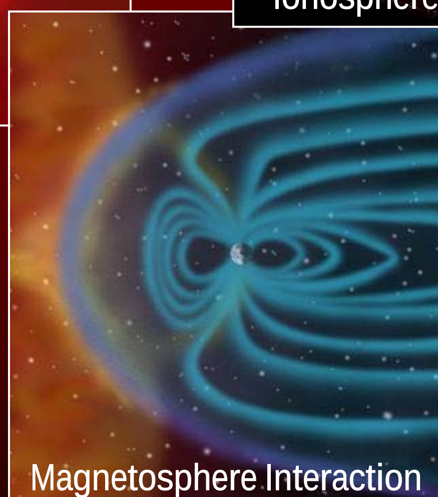
Dept. of Electrical and Computer Engineering
Mississippi State University
Box 9571
Miss. State, MS 39762

donohoe@ece.msstate.edu

Complete GIC Physics – Key Components







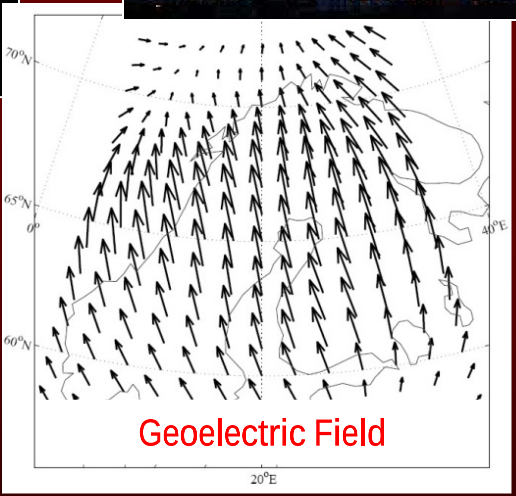


Image sources – http://www.nasa.gov
Thomson et al, Acta Geophysica, Vol. 57, no. 1

GIC Modeling Tools/Techniques

Modeling Tool/Technique **(Code classifications are generalized, actual code configurations vary)**	CME / Solar Wind	Magnetosphere Interaction	Ionosphere Electrodynamics	Geoelectric Field	System GIC
SWMF (Space Weather Modeling Framework, BATS-R-US)	●	●	●		
OpenGGCM (Open Geospace General Circulation Model)		●	●	○	
CMIT (Coupled Magnetosphere-Ionosphere-Thermosphere)		●	●		
TIEGCM (Thermosphere-Ionosphere Electrodynamics General Circulation Model)		●	●		
RCM (Rice Convection Model)		●			
LFM (Lyon-Fedder-Mobary Global MHD Model)		●			
Hakamada-Akasofu-Fry (HAFv2) Kinematic Solar Wind Model	●				

GIC Modeling Tools/Techniques

Modeling Tool/Technique **(Code classifications are generalized, actual code configurations vary)**	Coronal Mass Ejection	Magnetosphere Interaction	onosphere Electrodynamics	Geoelectric Field	System GIC
Weimer (2005)			●		
Weimer (2010)			●		
Real Time GIC Simulator (NRCan/FMI/Hydro One)				○	●
PowerWorld				○	●
OpenDSS (Distribution System Simulator)				○	●
PSS®E (Power System Simulator for Engineering – Siemens)				○	●
GICNow (Finish Meteorological Institute)				●	●

Sources for GIC Model Inputs

- Ground-based sensors
  - Magnetometers
  - Radars
  - Solar observatories
- Satellite-based sensors
  - Magnetometers
  - Electric field sensors
  - Radars
  - Imagers (optical, UV, X-ray, etc.)
  - Particle detectors, mass spectrometers

Determination of Ionosphere Currents

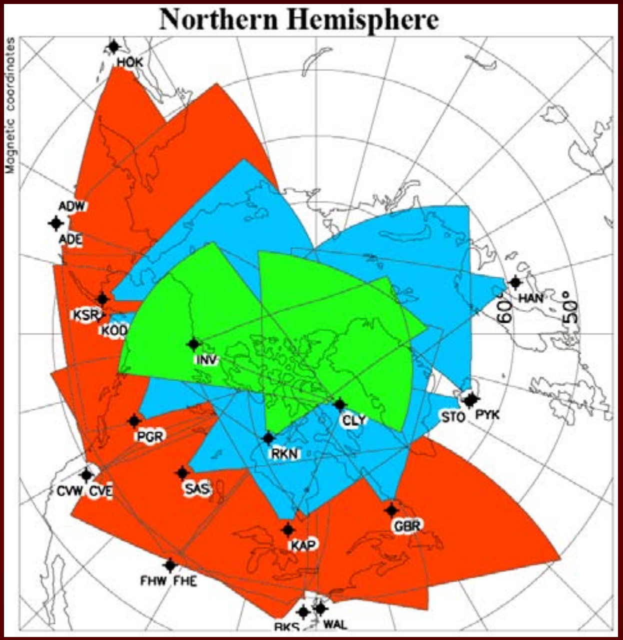
- Ionosphere currents are most often determined by an inverse problem using ground magnetometer data sets (determine equivalent currents that best match the magnetic fields at the discrete measurement locations).
- Ionosphere current models determined by inversion are not actual currents.
- The ionosphere potential can be determined using HF radar, from which currents can be determined. However, accurate knowledge of the ionosphere conductivity is required (difficult to measure, accuracy in question).

Ground Based Magnetometer Data

- Super MAG
  - Global network of over 300 magnetometers
  - Uniform coordinate system, time resolution and baseline removal
- INTERMAGNET
  - Global network of 133 magnetometers
- IMAGE (International Monitor for Auroral Geomagnetic Effects)
  - Network of 31 magnetometers (Norway, Sweden, Finland, Estonia, Russia)
- United States Geological Survey (USGS)
  - Network of 14 observatories across US
- Geological Survey of Canada (GSC)
  - Network of 13 observatories across Canada

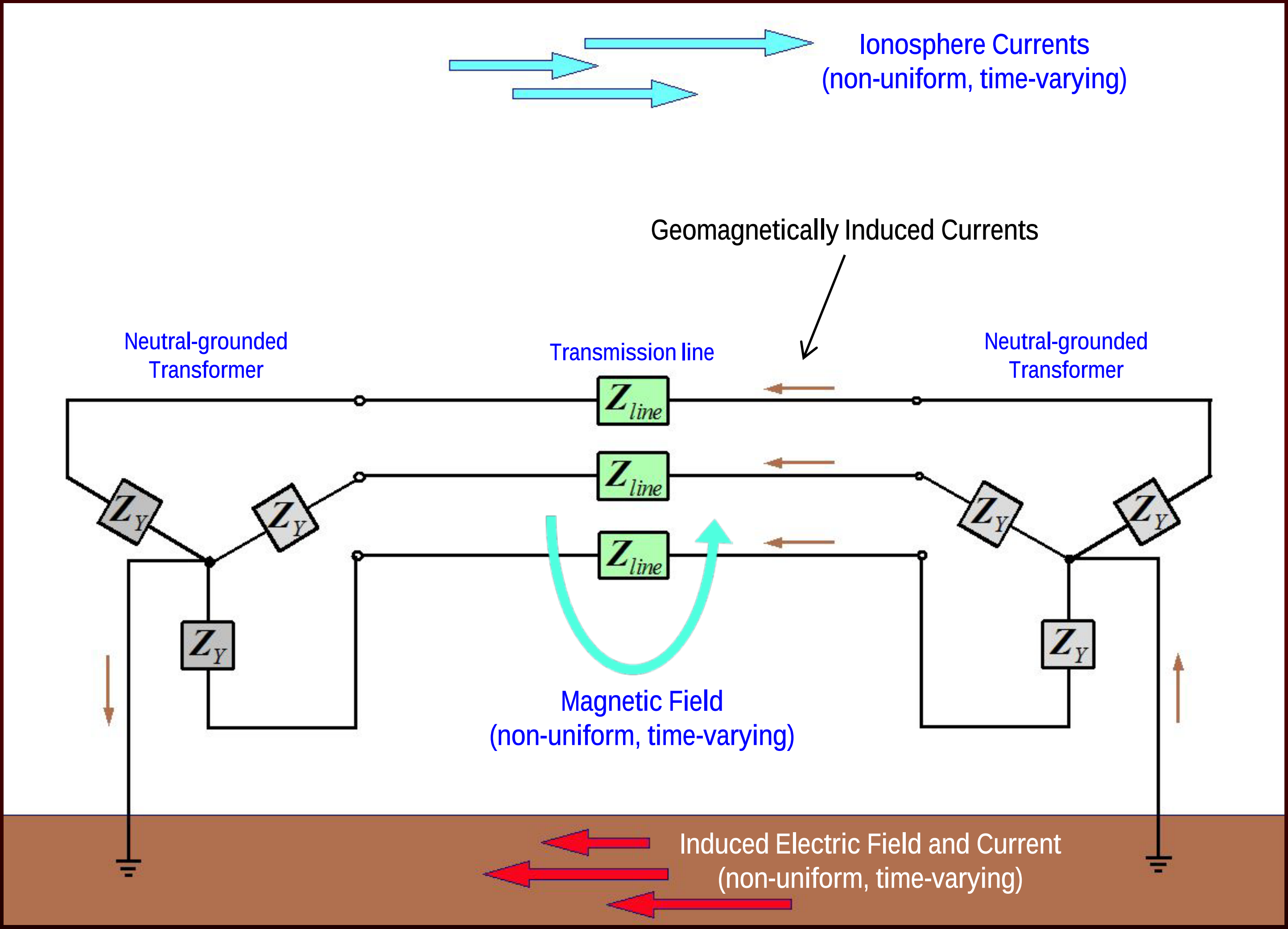
Radar Data

- Super Dual Auroral Radar Network (SuperDARN)
- 30 low power HF radars (8-20 MHz)
- Northern and southern hemispheres
- Continuous operation
- Monitor charged particles (plasma) in ionosphere



sources – http://sd-software.ece.vt.edu/tiki/tiki-index.php
http://superdarn.jhuapl.edu/index.html

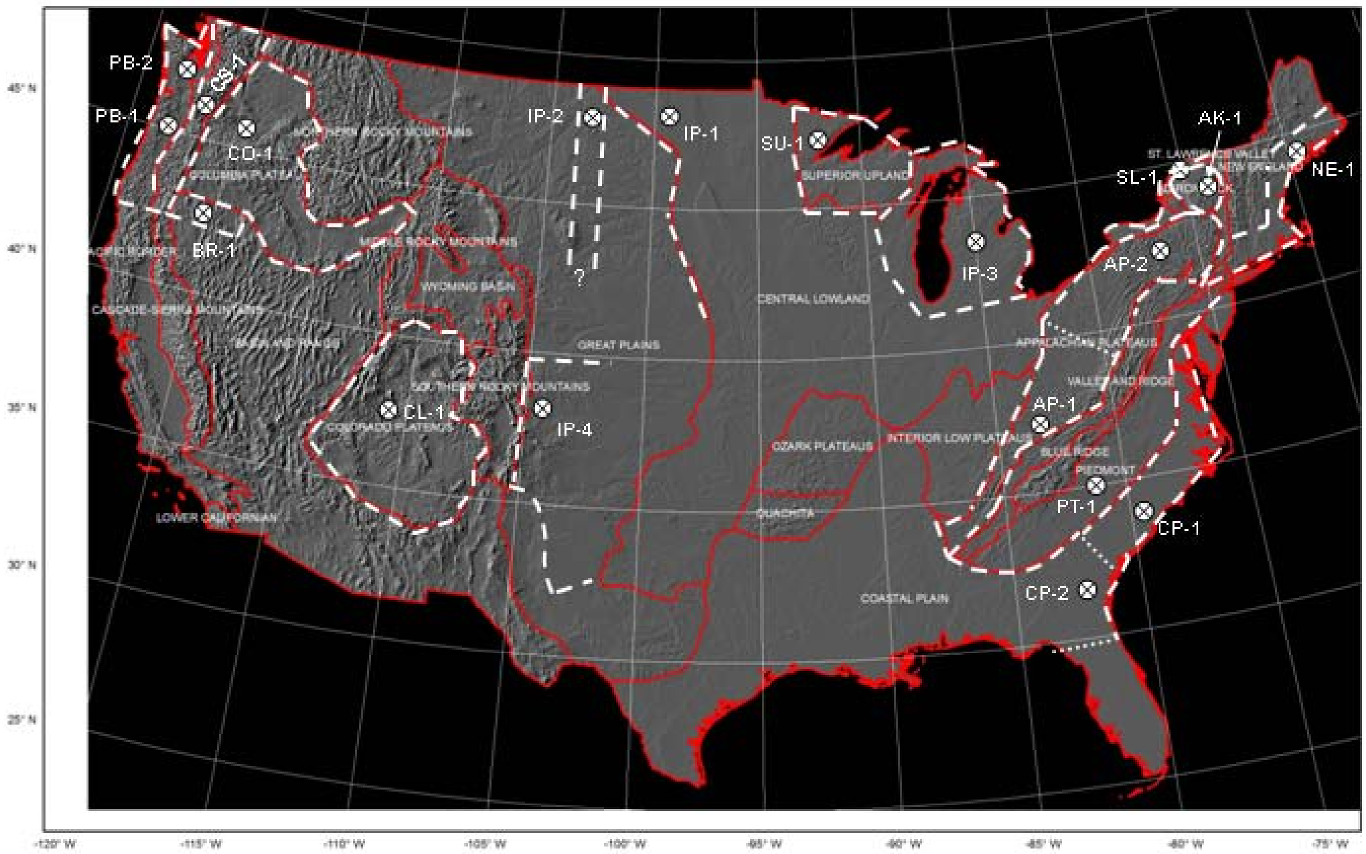
GIC Physics – Coupling of Geomagnetic Disturbances to Power Systems



Role of Ground Conductivity

- The geoelectric field and resulting GICs are proportional to dB/dt (characterized as quasi-DC at sub 1 Hz frequencies).
- The typical skin depth of a multilayered earth is on the order of 100's of kilometers at GIC frequencies.
- Conductivity models at depth are necessary to accurately determine the resulting geoelectric field produced by the ionosphere currents.

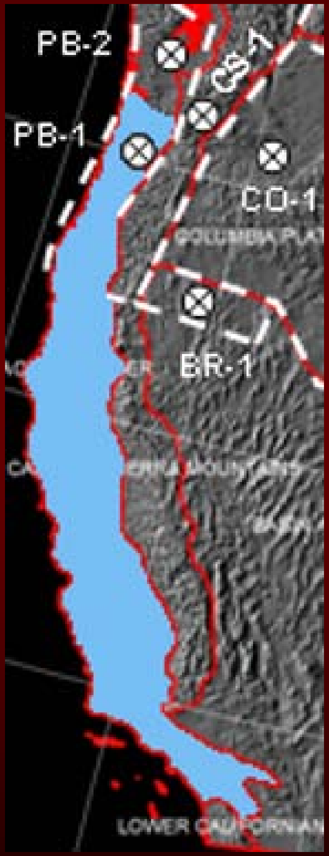
Location of 1D Earth Resistivity Models with respect to Physiographic Regions of the USA

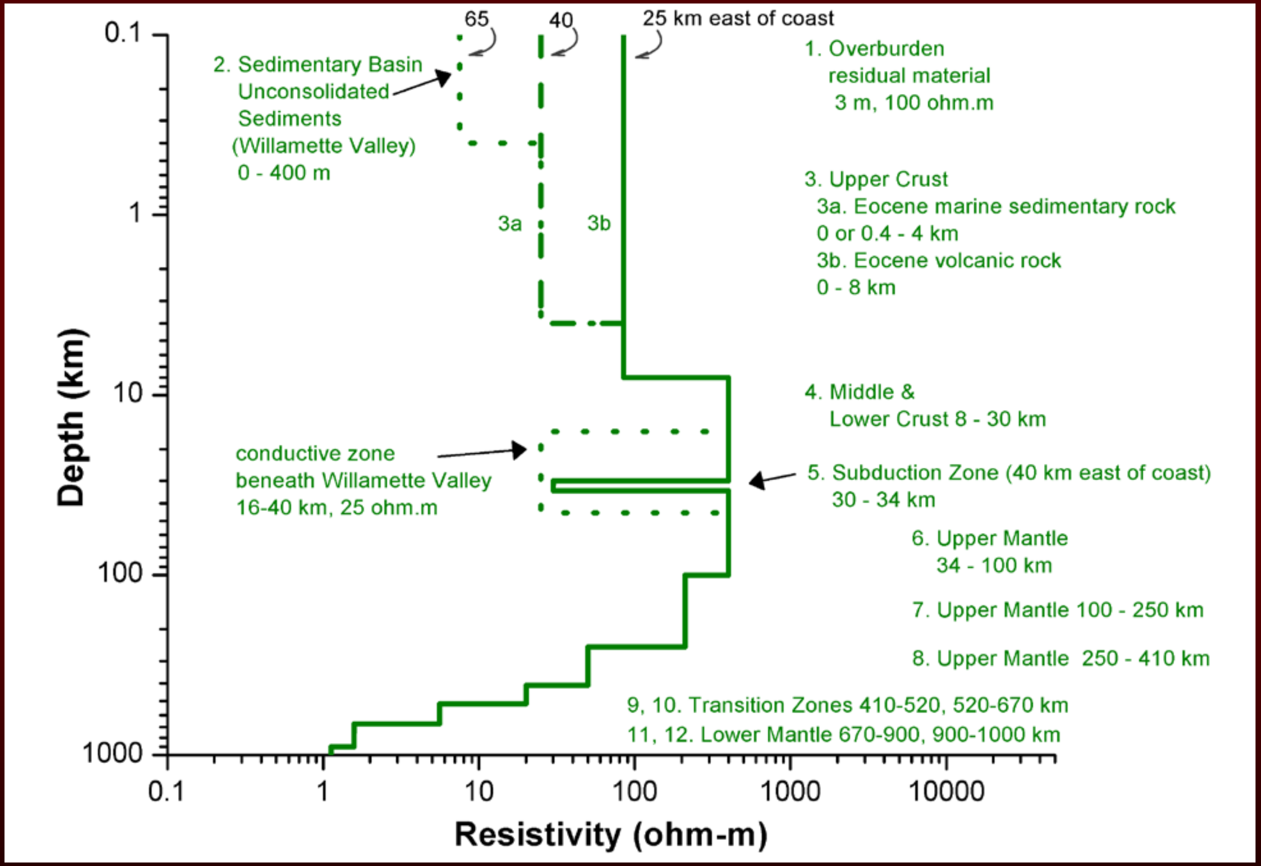


source – http://geomag.usgs.gov/conductivity/

Ground Conductivity Data

1D Resistivity Model for Pacific Border Model PB-1





source – http://geomag.usgs.gov/conductivity/

Impacts of Geoelectric Field Accuracy in GIC Calculations

- The induced voltages between ground points in the system are determined by integrating the geoelectric field along the transmission line conductors.

$$V_{ab} = \int_a^b \boldsymbol{E}_{geo} \cdot d\boldsymbol{l}$$

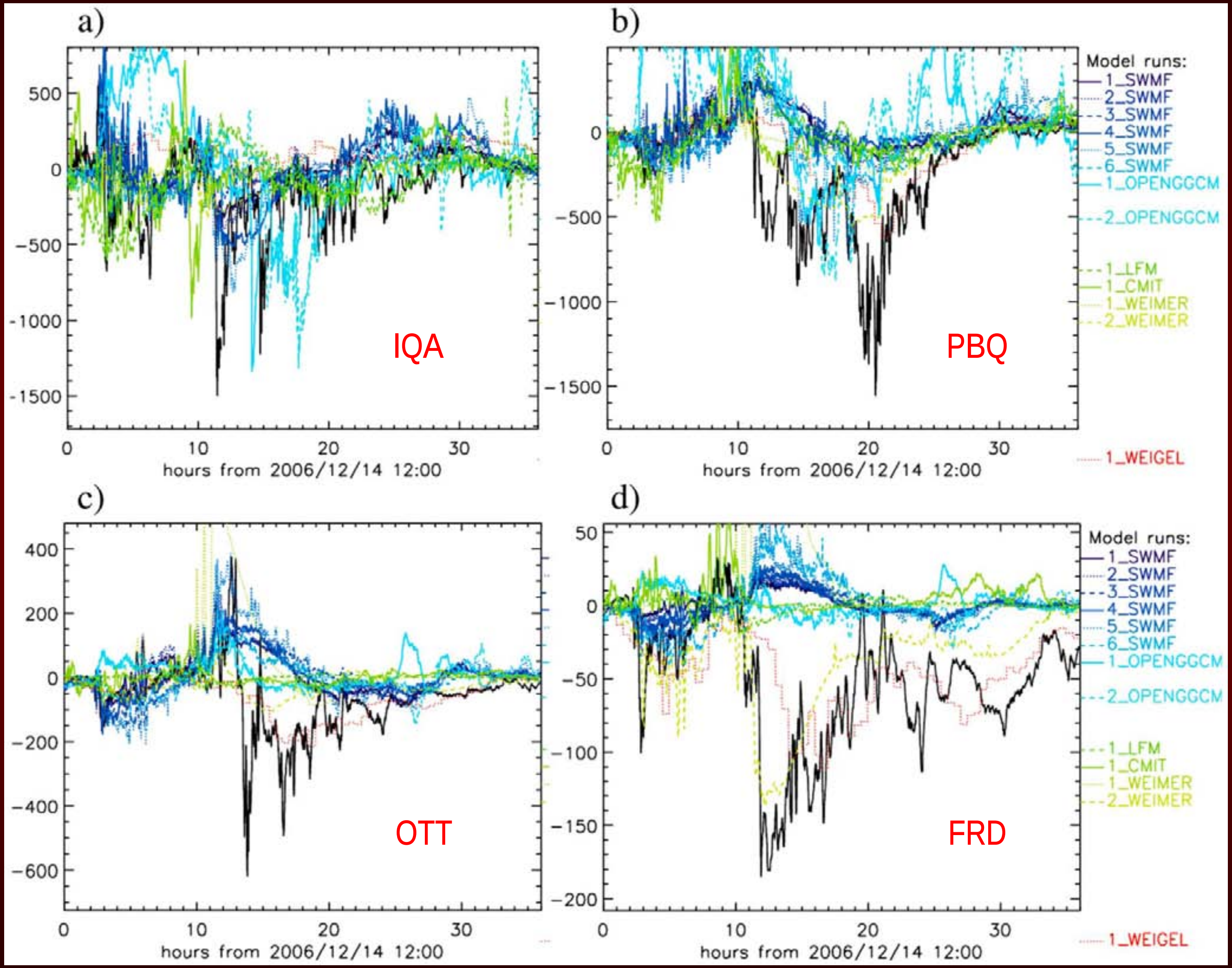
  - Geoelectric field is typically assumed to be uniform and unidirectional along entire conductor length.
  - Variation in the geoelectric field magnitude and direction along the conductor can impact the predicted GIC level.
- Horizontal discontinuities in the multilayered earth conductivity introduce significant variation on the geoelectric field (coastal effect).

GIC Models vs. Measurements

Geospace Environment Modeling 2008-2009 Challenge

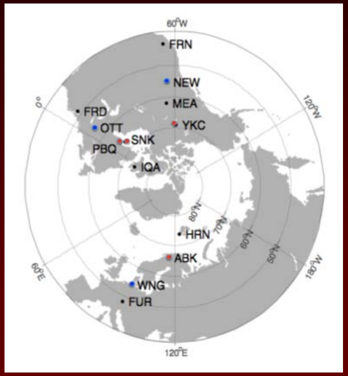
- A metrics challenge for space weather models
- Metrics were focused on inner magnetosphere dynamics and resulting changes in the ground magnetic field
- Final results from 14 models presented in 2011
- Four storm events were modeled:
  - Two major CME-related storms
    - 29-30 Oct 2003, 14-16 Dec 2006
  - Two storms based on less significant solar events
    - 31 Aug – 1 Sep 2001, 31 Aug – 1 Sep 2005
- Key model outputs relative to GIC are the ground magnetic field perturbations

- Simulated ground magnetic field perturbations (nT) at four stations.
- Dec 2006 storm
- The black lines are the measured fields.

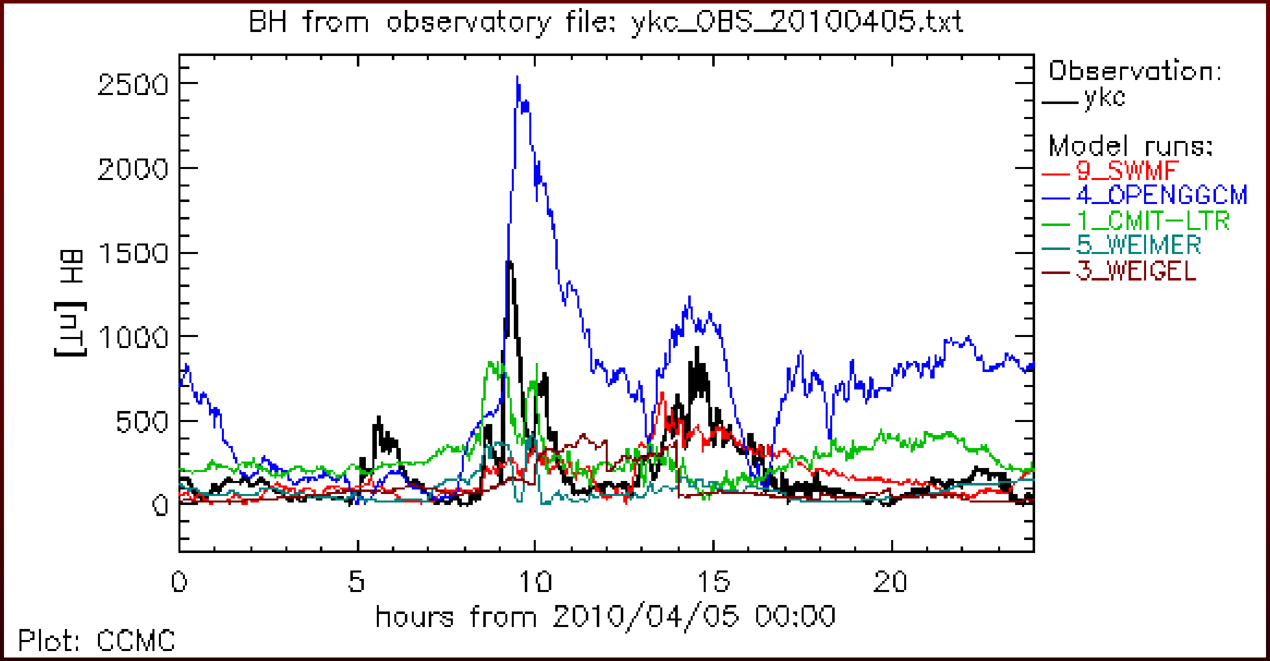


Source: Pulkkinen et al, Space Weather, Vol. 9, SO2004, 2011.

dB/dt Simulation vs. Measurement



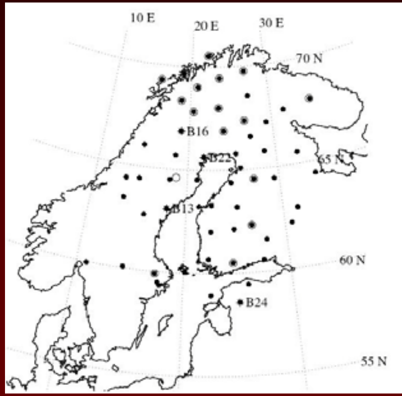
- Simulated derivative of horizontal ground magnetic field perturbations
- Black line – measured value
- First principles models (magnetosphere and ionosphere electrrodynamics)
  - SWWF, OpenGGCM, LFM (CMIT)
- Statistical models (magnetic perturbation models)
  - Weimer, Weigel

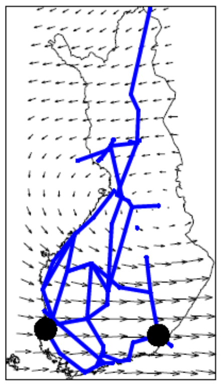


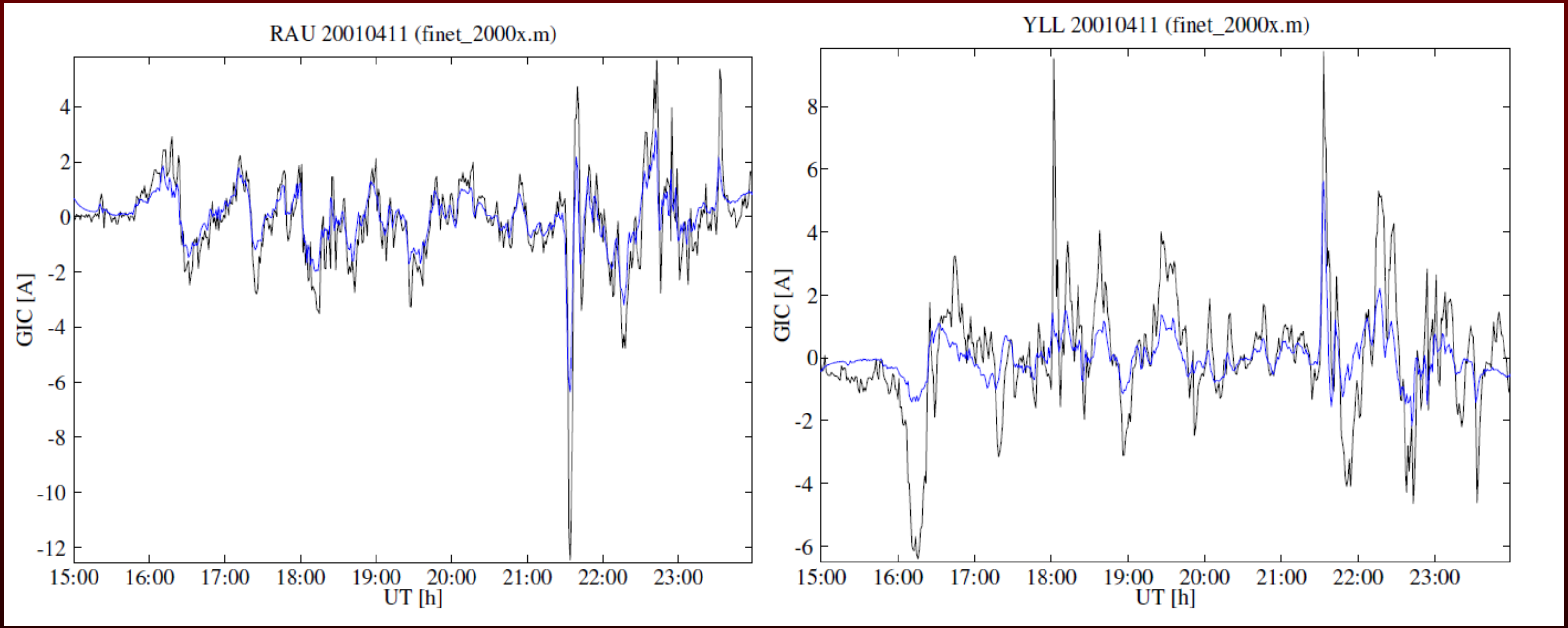
Source: Rastaetter et al, 2012 GEM Summer Workshop

GIC Simulation vs. Measurement

- GIC measured on Finnish power system at two 400 kV transformer stations
- Ionosphere current model based on local magnetometer measurements
- Dense set of 22 observatories
- Measured GIC - black lines, simulated GIC – blue lines
- 11 April 2001 storm







Source: Viljanen et al, Annales Geophysicae (2004) 22: 101-113.

Conclusions

- Accurate simulation results for GIC levels in power systems requires a large model incorporating complex geometry and complex physics.
- From the engineering perspective, a model based on accurate ionosphere currents determined from measurements shows the most promise (bypassing the CME, solar wind and magnetosphere physics).
- More magnetometer sites would enhance the accuracy of the ionosphere current in a model based on the inverse technique.
- Accurate GIC simulations for a wide range of scenarios will likely require the use of a more accurate (non-uniform) geoelectric field.

Questions?